Ecological Engineering 35 (2009) 1758–1772

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Effects of projected future urban land cover on nitrogen and phosphorus runoff to Chesapeake Bay

Allen D. Roberts[a,*], Stephen D. Prince[a], Claire A. Jantz[b], Scott J. Goetz[c]

[a] Department of Geography, University of Maryland, 2181 LeFrak Hall, College Park, MD 20742, USA
[b] Department of Geography and Earth Science, Shippensburg University, 1871 Old Main Drive, Shippensburg, PA 17257, USA
[c] Woods Hole Research Center, 149 Woods Hole Road, Falmouth, MA 02540, USA

ARTICLE INFO

Article history:
Received 27 January 2009
Received in revised form 1 September 2009
Accepted 14 September 2009

Keywords:
Chesapeake Bay
Estuaries
Landscape metrics
Nutrients
Projected urbanization
Riparian stream buffers
Remote sensing
Rivers/streams
SLEUTH model
SPARROW model
Watershed management

ABSTRACT

This paper examined the effects of simulated land cover/land use (LC/LU) change from 2000 to 2030 on nutrient loadings to the Chesapeake Bay. The *SPA*tially *R*eferenced *R*egression *O*n *W*atershed Attributes (SPARROW) model was used with anticipated watershed-wide LC/LU change from a growth forecast model that provides spatially explicit probabilities of conversion to impervious surface. The total nitrogen (TN) and total phosphorus (TP) loadings estimated to enter the Chesapeake Bay were reduced by 20% and 19%, respectively. In general, as development replaced other LC/LUs from 2000 to 2030, TN and TP runoff was significantly reduced by losses of non-point, non-urban source loadings, yields, and land-to-water delivery. The simulation results suggest future changes in landscape composition and configuration at catchment and riparian stream buffer width scales could lower TN and TP runoff to the estuary.

1. Introduction

Urbanization is a primary form of land cover/land use (LC/LU) change that is accelerating and has significant influence on watershed-wide environmental conditions. Urbanization converts croplands, forests, grasslands, pastures, wetlands, and other cover types to, in particular, residential and transportation, but also commercial and industrial uses, increasing significantly areas of impervious surfaces (Tsegaye et al., 2006). Globally, as population increases and shifts from rural areas to cities, urban expansion is inevitable. Furthermore, within the United States, population and its associated development is growing twice as fast in coastal areas as compared to inland areas (Bartlett et al., 2000; Conway and Lathrop, 2005). As urban land cover continues to increase, the incidence of non-point (diffuse) source nutrients, such as nitrogen (N) and phosphorus (P), in streams from impervious cover can be expected to rise significantly. These nutrients travel from land surfaces to streams as eroded organic and dissolved inorganic species via overland, shallow interflow, and even baseflow runoff processes. Excess nutrients are the main causes of eutrophication, hypoxia, and anoxia in rivers, estuaries, and coastal oceans (Paerl, 2006). Thus, the impacts on nutrient loading (mass for a specified time) estimates within rivers, estuaries, and coastal oceans of projected future urban growth are of interest. Some studies have examined scenarios of future urbanization on non-point source N and P in smaller watershed regions (Tsihrintzis et al., 1996; Bhaduri et al., 2000; Costanza et al., 2002; Chang, 2004; Filoso et al., 2004; Tang et al., 2005; Wang et al., 2005), however larger regions have not been studied thoroughly, yet significant impacts on regional, national, and even global nutrient loadings can be expected.

To quantify the potential future nutrient loadings of a significant larger region, the Chesapeake Bay watershed was examined. The Chesapeake Bay is the largest estuary in the United States, with a watershed (166,534 km^2) encompassing portions of six states (New York (NY), Pennsylvania (PA), Delaware (DE), Maryland (MD), West Virginia (WV), and Virginia (VA)) and the District of Columbia (DC) (Fig. 1a and b). The Chesapeake Bay also has the highest watershed land area per volume of water of any estuary in the United States, making runoff from the land surface critically important in

* Corresponding author. Tel.: +1 301 633 5397; fax: +1 301 314 9299.
E-mail address: allenr@umd.edu (A.D. Roberts).

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doi:10.1016/j.ecoleng.2009.09.001

determining the nutrient status of the estuary (Shuyler et al., 1995). While human-induced LC/LU transformations that lead to increases in Bay N and P first appeared in the watershed in the mid-1600s (Boesch, 2006), this rate increased after the end of World War II in the late 1940s when the Chesapeake Bay population was still under 8 million (McConnell, 1995). By 2000, the watershed's population was approximately 15.7 million (Chesapeake Bay Program, 2008a), with expectations of close to 20 million by 2030 (Chesapeake Bay Program, 2008b). Clearly this increase will further drive human-induced LC/LU changes in the form of urbanization. Increases in nutrient delivery to the estuary resulting from these population and consequent LC/LU changes have been the primary focus of research and policy efforts relating to restoring the Chesapeake Bay through the Federal Water Pollution Control Act (FWPCA) of 1972 and the Clean Water Act (CWA) of 1977 (Morgan and Owens, 2001). Thus, watershed-wide examinations of projected future urbanization on delivered N and P loadings to the estuary are warranted.

The spatial pattern of urban development in the Chesapeake Bay watershed is increasingly taking the form of low-density, decentralized residential and commercial development (Jantz et al., 2004). Previous research has indicated that between 1970 and 2000, lot sizes throughout the watershed increased by 60% and that the average home size also increased from 1500 to 2265 ft^2 (Chesapeake Bay Program, 2008c). These trends are expected to continue over time (Chesapeake Bay Program, 2008c). It is reasonable to assume that water quality and aquatic habitats in the watershed will decline due to this urbanization, but low-density development may have less effect than earlier, more concentrated expansion. Projection of the current trend of growth to 2030 may provide a better insight into the probable effects on the Chesapeake Bay nutrient status.

Watershed-wide, spatially explicit, predictions of urbanization with 30 m resolution have been modeled by Jantz et al. (submitted for publication) using the *S*lope, *L*anduse, *E*xclusion, *U*rban extent, *T*ransportation, and *H*illshade (SLEUTH) urban growth model. SLEUTH is a cellular automaton, pattern-extrapolation model calibrated using urban development patterns in the past and forecasts of these patterns into the future (Jantz and Goetz, 2005). This version of SLEUTH was developed from the Clarke urban growth (Clarke et al., 1997) and land cover change models (United States Geological Survey, 2008a). SLEUTH has been applied to model urban growth in numerous areas (Clarke and Gaydos, 1998; Silva and Clarke, 2002; Arthur-Hartranft et al., 2003; Herold et al., 2003; Yang and Lo, 2003; Dietzel and Clarke, 2004; Solecki and Oliveri, 2004; Xian and Crane, 2005; Xian et al., 2005). In addition to the Jantz et al. (submitted for publication) recent application of SLEUTH to the entire Chesapeake Bay watershed, the model has been previously applied (although to smaller regions) in the watershed near Baltimore (MD), DC, and State College (PA) (Clarke and Gaydos, 1998; Carlson, 2004; Jantz et al., 2004; Claggett et al., 2005).

Increases in impervious surface areas may contribute more N and P to the Chesapeake Bay as a result of increases in leaf litter, vehicle emissions, residential and roadside landscaping (fertilizers), urban wildlife and pets, construction, and infrastructure (Minton, 2002).

The projected effects of watershed-wide urban growth and consequent effects on LC/LU and its changes on nutrient loadings were estimated using the United States Geological Survey's (USGS) *SPA*tially *R*eferenced *R*egressions *O*n *W*atershed *A*ttributes (SPARROW) model (Smith et al., 1997; Schwarz et al., 2006). SPARROW estimates total nitrogen (TN) and total phosphorus (TP) runoff from watersheds of various sizes by statistical functions that relate

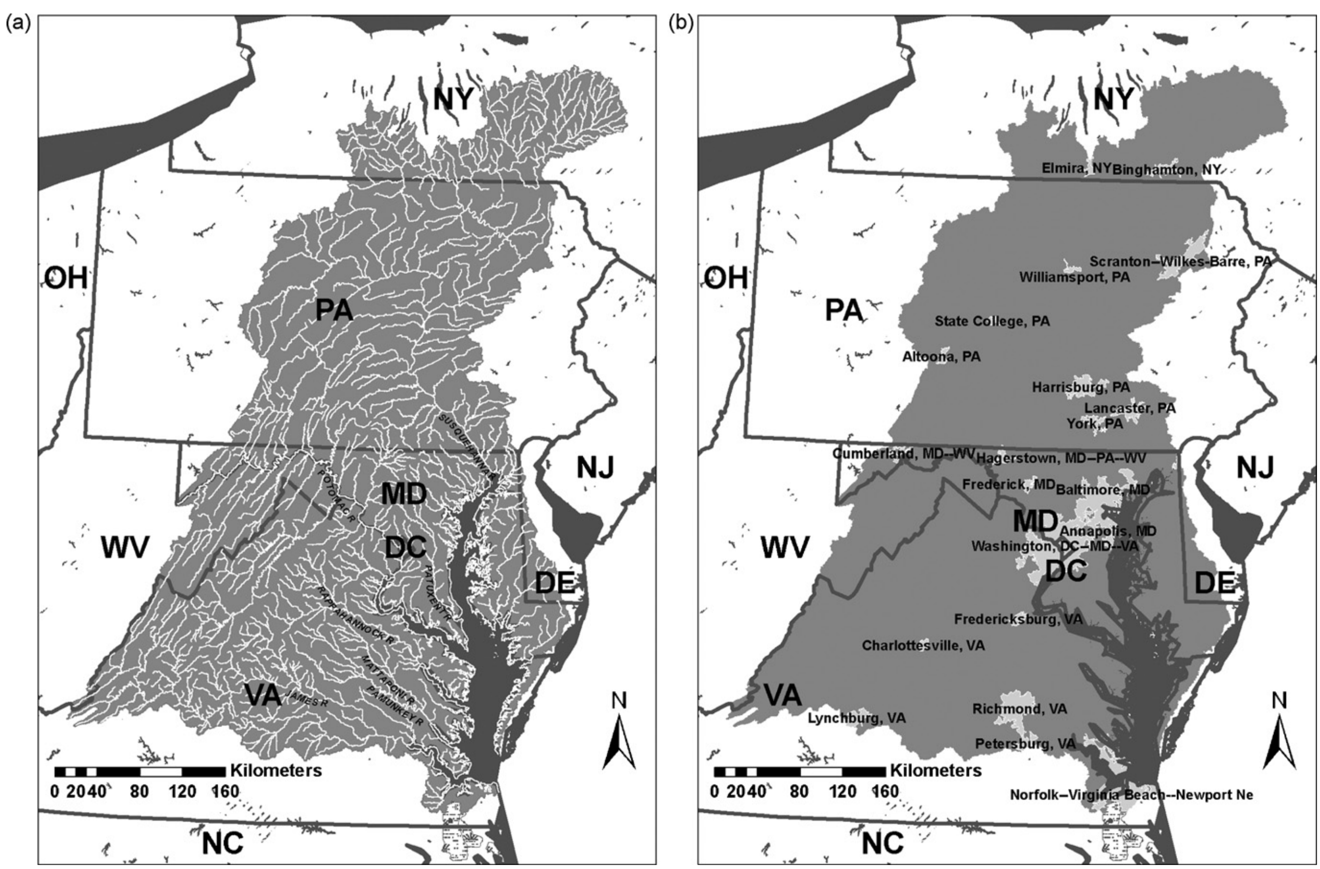

Fig. 1. The Chesapeake Bay watershed showing the locations of (a) streams and rivers draining the estuary and (b) urban centers located within its boundaries.

upstream point and non-point sources, land-to-water delivery variables, and stream and reservoir nutrient attenuation (loss) processes that change TN and TP loadings as they travel downstream through nested river channel and reservoir networks. Quantities of contaminants in streams may be expressed as either loadings or yields (mass loading normalized by drainage area). Land-to-water delivery variables describe properties of the landscape relating climatic, natural, and human-induced surface processes affecting non-point N and P transport to streams.

The hybrid statistical-process structure of the model allows for the implementation of deterministic functions (such as first-order stream loss functions) with spatially distributed components (such as sources and land-to-water delivery variables within stream networks) to account for the dendritic nature of watersheds (Alexander et al., 2002). SPARROW is based upon an average year and does not account for individual storms (that is, it is not event-based). The model simulates average annual discharge in terms of loadings and yields locally generated and delivered to the estuary, using just those input variables that have significant effects (p-value ≤ 0.05). Local generation is the amount of TN or TP generated from within each catchment independent of any upstream loadings or yields, whereas delivered refers to the amount of TN or TP reaching the estuary after accounting for any upstream loadings and yields and also in stream and reservoir losses. The model is applied to each of 2339 catchments of the Chesapeake Bay watershed (Fig. 2a) using a watershed map by Brakebill and Preston (2004). The model has been applied to the Chesapeake Bay watershed using the National Land Cover Dataset (NLCD) (Preston and Brakebill, 1999; Brakebill et al., 2001; Brakebill and Preston, 2004) and by Roberts and Prince (in press) incorporating the *R*egional *E*arth *S*cience *A*pplication *C*enter's (RESAC) remotely sensed LC/LU and percent impervious surface area (% ISA) maps for 2000 (Goetz et al., 2003, 2004a,b; Jantz et al., 2005).

Roberts and Prince (in press) used entire catchment and 31 m riparian stream buffer landscape metrics to specify non-point sources and land-to-water delivery variables that affect TN and TP loadings to the Chesapeake Bay. Landscape metrics describe the spatial structure of patches, the cover classes of patches, and patch mosaics, thus providing measures of composition (the variety and abundance of patch types) and configuration (spatial character and arrangement, position, and orientation of landscape elements (Leitao et al., 2006)). The use of landscape metrics, in conjunction with projected future urban growth, has previously indicated that spatial alterations in LC/LU affect predicted N and P loadings in streams throughout a significant portion of Chesapeake Bay watershed (Wickham et al., 2002), although a holistic watershed approach was not implemented. Even in remote reaches of the watershed, locally dependent land development decisions that lead to more urban growth can adversely affect downstream loadings to the estuary. Thus, holistic watershed management is needed to bridge this gap between land use planning and comprehensive natural resource management (Conway and Lathrop, 2005). Modeling is needed to integrate the local catchment level to impacts on the entire Chesapeake Bay watershed.

Thus, the overall purpose of this study was to estimate future TN and TP runoff to the Chesapeake Bay, using SPARROW models, with maps of projected future urbanization.

2. Materials and methods

2.1. Future Chesapeake Bay watershed land cover and land use

Maps of the projected development in 2030 were derived from SLEUTH model runs for the Chesapeake Bay watershed (Jantz et al., submitted for publication). The model was calibrated with growth and changes in land use for several dates between 1986 and 2000, utilizing a time series of Landsat Thematic Mapper (TM) satellite imagery. Landsat TM data have a spatial resolution of 30 m × 30 m (900 m^2) and so the map of development was spatially explicit at this scale for the entire watershed. The inputs used in the calibration of the model were (1) historic urban extent for 1986, 1990, 1996, and 2000; (2) historical transportation networks (roads) for 1986 and 1996; (3) a USGS digital elevation model (DEM) representative of slope, and (4) an excluded layer representative of non-developable land areas (Woods Hole Research Center, 2009). The exclusion layer consisted of probabilities of development for water (zero, that is 100% excluded), areas affected by growth-reduction policies ("smart growth" non-priority funding areas), and federal, local, and state parks (80% excluded) based upon some limited development that had occurred in these regions previously. Different exclusion probabilities were used to represent different future planning policies; in this study the "business as usual" or "current trends" scenario was used to represent current policies that are already in place and their consequent probabilities of development. The current trends scenario also allowed areas on the urban fringe that are currently non-urban to be developed (Jantz et al., 2004). During calibration, growth parameters (spontaneous, new spreading centers, edge, and road-influenced) were intersected with the exclusion layers to model urbanization between 1986 and 2000. Testing the model included comparison with the actual development that has taken place between 1986 and 2000. Overall accuracy at the pixel scale was 93.1% and Hydrologic Unit Code (HUC)-11 watershed and county scales gave r^2 values of 0.72 and 0.86, respectively (Woods Hole Research Center, 2009).

The parameterized SLEUTH model was then used to make projections of the probabilities of development as represented by the impervious surface area (ISA) at the 30 m × 30 m (900 m^2) pixel scale for the entire Chesapeake Bay watershed-wide by 2030. The probabilities were converted to a binary classification of urban (≥10% ISA) (class 1) and non-urban (<10% ISA) (class 2). Class 2 pixels were assumed to remain in their existing 12 LC/LU classes, as given by the 2000 RESAC LC/LU map (Goetz et al., 2004a,b; Jantz et al., 2005). All 14 LC/LU used in this study are given in Table 1. Complete accounts of the LC/LU mapping methodologies are given in Goetz et al. (2004b) and Jantz et al. (2005). Ten 2030 SLEUTH map runs were averaged to create mean values of 2030 LC/LU.

Table 1
The fourteen Chesapeake Bay watershed land cover classes used.

2030 Land cover class	Class number
Urban	1
Non-urban	2
Urban/residential/recreational grasses	3
Extractive	4
Barren	5
Deciduous forest	6
Evergreen forest	7
Mixed (deciduous-evergreen) forest	8
Pasture/hay	9
Croplands	10
Natural grass	11
Deciduous wooded wetland	12
Evergreen wooded wetland	13
Emergent (sedge-herb) wetland	14

2.2. Landscape metrics and Chesapeake Bay SPARROW models

The models used here addressed some shortcomings of previous Chesapeake Bay TN and TP SPARROW models (Preston and Brakebill, 1999; Brakebill et al., 2001; Brakebill and Preston, 2004), including: adding a relationship between LC/LU composition and

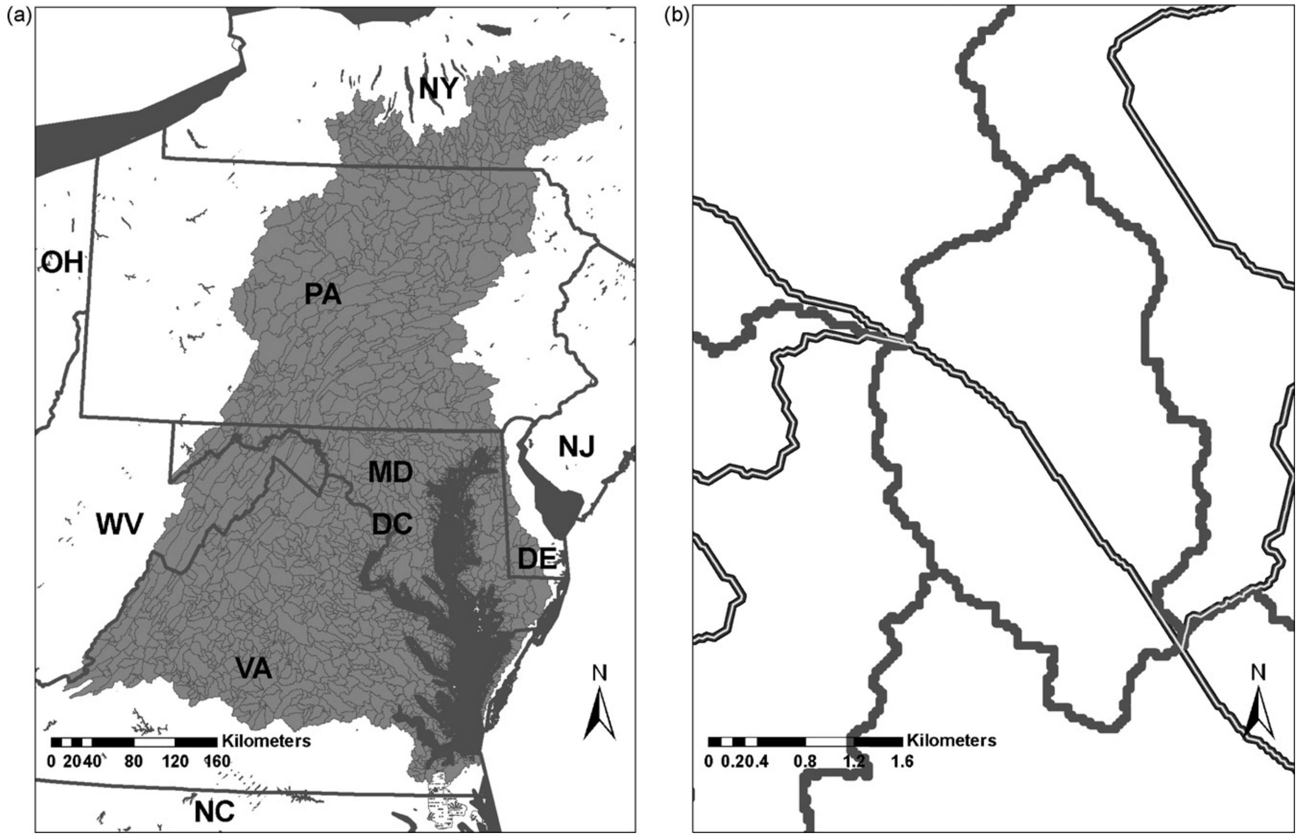

Fig. 2. Map of (a) 2339 United States Geological Survey (USGS) Chesapeake Bay total nitrogen (TN) and total phosphorus (TP) *SPA*tially *R*eferenced *R*egressions *O*n *W*atershed Attributes (SPARROW) model catchments used and (b) example Chesapeake Bay catchment with fixed riparian stream buffer width area of 31 m surrounding stream reach.

the land-to-water delivery of non-point N and P; consideration of landscape configuration; and other spatial configuration factors such as LC/LU in riparian zones. Roberts and Prince (in press) found that LC/LU composition and configuration in catchments and composition in riparian buffers improved the precision of TN and TP loadings estimates for 2000. A complete account of the definitions, techniques, and other methods used regarding the incorporation of landscape metrics and the 2000 SPARROW model calibrations is given in Roberts and Prince (in press).

In the 2000 RESAC 31 m models, five metrics (1–3, 6,7) measuring landscape composition and two metrics (4–5) measuring configuration (Leitao et al., 2006) were initially evaluated in SPARROW for each catchment to quantify the effects of non-urban and urban land cover on current TN and TP runoff to the Chesapeake Bay. The following summaries indicate the properties that each metric measures. Complete definitions for all seven metrics are given in Leitao et al. (2006).

(1) *Contagion* quantifies the degree to which LC/LU types were clumped in larger patches as opposed to dispersed in many smaller fragments.
(2) *Area-weighted mean radius of gyration* measures connectivity using correlation length. This is the average distance one might traverse across a map from a random starting point and moving in a random direction while remaining in the patch.
(3) *Patch number* indicates total number of patches of a particular LC/LU.
(4) *Percentage of the landscape* area composed of a specified LC/LU.
(5) *Area-weighted mean patch size* quantifies the sum, across all patches of a particular LC/LU, of patch area multiplied by proportional abundance of the patch.
(6) *Area-weighted mean edge contrast* quantifies the amount of contrast between adjacent LC/LU patches. In this application, contrast is defined as physical characteristics of differing cover types that may influence nutrient transport and delivery.
(7) *Area-weighted mean Euclidean nearest neighbor distance* quantifies the shortest distance from one patch to the next patch of the identical LC/LU type.

All area-weighted mean landscape metrics weight each patch by its size relative to the total area of that specific LC/LU, meaning that larger patches will exert greater influence than smaller patches and they are insensitive to extremely small patches.

Of the seven landscape metrics analyzed, only three (4–6) were found to be significant in the 2000 models (Table 2) and so the others were excluded. Thus, the SPARROW models were based upon landscape metrics for LC/LU in whole catchments and in just a 31 m riparian stream buffer. Riparian stream buffers are defined here as fixed, transitional areas between terrestrial landscapes and stream reaches created from the linked, spatially referenced watershed network (Fig. 2b). Non-point sources and land-to-water delivery variables from the models calibrated with 2000 data (Roberts and Prince, in press) were used to model future Chesapeake Bay TN and TP loadings using maps of LC/LU classes in 2030.

The predictor variables (Table 2) used in the 2000 models are described below; for further details see Roberts and Prince (in press). In the TN model, for each kg of (1) point sources discharged, (2) fertilizer and (3) manure applied to agricultural land (crop and pasture) and (4) atmospheric N deposited on the watershed, approximately 1.2, 0.2, 0.1, and 0.5 kg of N, respectively, were estimated in Chesapeake Bay streams annually. For each hectare (ha) of (5) area-weighted mean urban patch size, nearly 25 kg of N was estimated in Chesapeake Bay streams annually. Urban patch size

Table 2
All significant (p-value < 0.05) variables in the 2000 Regional Earth Science Applications Center (RES AC) 31 m total nitrogen (TN) and total phosphorus (TP) *SPAt*ially Referenced Regressions On Watershed Attributes (SPARROW) models (Roberts and Prince, in press). RMSE = root mean squared error.

Model component (units)	TN model Yield R^2 = 0.9366 RMSE = 0.2406			TP model Yield R^2 = 0.7503 RMSE = 0.3216		
	Variable	Coefficient value	p-Value	Variable	Coefficient value	p-Value
Source	Point[a]	1.173	1.2×10^{-4}	Point[a]	0.738	1.3×10^{-6}
	Applied fertilizer[a]	0.175	3.9×10^{-6}	Applied fertilizer[a]	0.016	1.1×10^{-3}
	Atmospheric deposition[a]	0.492	2.0×10^{-7}	Applied manure[a]	0.008	3.0×10^{-2}
	Applied manure[a]	0.078	7.7×10^{-4}	Area-weighted mean non-agricultural/non-urban patch size[b,c]	0.110	5.8×10^{-13}
	Area-weighted mean urban patch size[b,c]	24.885	7.2×10^{-7}	Area-weighted mean urban patch size[b,c]	0.921	1.0×10^{-4}
Landscape delivery (%)	Percentage of coastal plain	−0.729	4.1×10^{-8}	Percentage of barren land within the riparian stream buffer[b]	0.281	1.2×10^{-6}
	Percentage of extractive land[b]	0.270	7.4×10^{-4}			
	Area-weighted mean edge contrast of deciduous forest[b]	0.014	7.2×10^{-3}			
	Percentage of cropland[b]	0.021	1.1×10^{-4}			
	Percentage of evergreen forest within the riparian stream buffer[b]	0.013	4.7×10^{-2}			
Stream decay (m/day)	Small streams	0.249	5.5×10^{-2}	Small streams	−0.198	1.3×10^{-1}
	Intermediate streams	0.090	3.2×10^{-1}	Intermediate streams	0.150	1.9×10^{-1}
	Large streams	0.030	4.8×10^{-1}	Large streams	0.034	5.2×10^{-1}
Reservoir decay (m/year)	Reservoir	14.224	2.3×10^{-2}	Reservoir	19.019	5.7×10^{-2}

[a] kg/year.
[b] All landscape metrics found to be significant.
[c] kg/ha/year.

(modeled by ISA) was used to estimate the buildup and washoff of N to sewers from urban non-point sources. For each percent of (6) land on the coastal plain, non-point N delivered to streams was estimated to decrease by 0.73% annually. Unlike the coastal plain, for each percent of (7) extractive, (8) cropland, and (9) area-weighted mean edge contrast of deciduous forest, non-point N delivered to streams was estimated to increase by 0.27%, 0.021%, and 0.014% annually, respectively. Area-weighted mean edge contrast of deciduous forest was used to measure the N transport differences between eleven non-urban classes and deciduous forest in the 2000 RESAC LC/LU map. Greatest differences between deciduous forest were with urban/residential/recreational grasses, extractive, barren, pasture/hay, croplands, and natural grass. For each percent of (10) evergreen forest in the riparian stream buffer, non-point N delivered to streams was estimated to increase by 0.013% annually. In the case of all four of these land-to-water delivery metrics, these variables estimate land properties (reduced hydraulic conductivities), associated with these or surrounding cover types at the soil and shallow subsurface scales, that increased N-enriched overland and shallow subsurface runoff. For every meter traveled in (11) small (mean flow ≤100 cubic feet per second (ft^3/s)), (12) intermediate (mean flow >100 and ≤500 ft^3/s), and (13) large (mean flow >500 ft^3/s) streams per day, about 25%, 9%, and 3% of the instream N was estimated to be lost, respectively. Finally, for any (14) reservoir in the watershed, an average depth of over 14 m of N was estimated to be deposited annually into the reservoir by the settling velocity.

In the TP model, for each kg of (1) point sources discharged, (2) fertilizer and (3) manure applied to agricultural land, approximately 0.7, 0.02, and 0.01 kg of P, respectively, were estimated in Chesapeake Bay streams annually. For each ha of (4) area-weighted mean non-agricultural/non-urban patch size, over 0.1 kg of P was estimated in Chesapeake Bay streams annually. This metric represented patches of mainly forest that exported P to streams as smaller predominant quantities of dissolved inorganic P via groundwater (baseflow) and shallow subsurface discharges. It was created by subtracting area-weighted mean cropland patch sizes from area-weighted mean non-urban patch sizes. For each ha of (5) area-weighted mean urban patch size, approximately 1 kg of P was estimated in Chesapeake Bay streams annually. For each percent of (6) barren land in the riparian stream buffer, non-point P delivered to streams was estimated to increase by 0.281% annually. This metric also represented reductions in hydraulic conductivity at the soil surface that increased P-enriched overland runoff. For every meter traveled in (7) small streams per day, an increase of about 20% P was estimated to occur, thus indicating small streams were a source by acting as a mechanism to erode P-enriched sediments. For each meter traveled in (8) intermediate and (9) large streams per day, about 15% and 3% of the instream P was estimated to be lost, respectively. Finally, for any (10) reservoir in the watershed, an average depth of over 19 m of P was estimated to be deposited annually into the reservoir also by the settling velocity.

Although some stream and reservoir decay coefficients have p-values >0.05 that indicate these variables are statistically insignificant, these variables are still included in model calibrations on the grounds of being mechanistically significant within the SPARROW model structure.

In all, five TN and three TP landscape metrics were significant non-point sources or land-to-water delivery variables in the model (Table 2) (Roberts and Prince, in press). The predicted values of these metrics in 2030 were calculated using forecasted 2030 LC/LU data (Table 1). ISA was modeled using SLEUTH while the other LC/LU classes in 2030 were estimated using the 2000 RESAC LC/LU map for all areas that were not predicted to become ISA.

Table 3
Comparison of 2000 and projected 2030 Chesapeake Bay watershed-wide total discharged point source and applied fertilizer and manure loadings (kg/year), land-based source variables (ha), and land-to-water delivery variables (%).

TN model					TP model				
Variable	2000	20	2030–2000 change	2030–2000 % change	Variable	2000	20	2030-2000 change	2030–2000 % change
Point	3.6605×10^7	4.8122×10^7	$+1.1517 \times 10^7$	+31.46	Point	2.6955×10^6	3.3730×10^6	$+6.7750 \times 10^5$	+25.13
Applied fertilizer	1.9346×10^8	7.6587×10^7	-1.1687×10^8	−60.41	Applied fertilizer	6.6409×10^7	3.6437×10^7	-2.9972×10^7	−45.13
Applied manure	8.7020×10^7	1.4673×10^8	$+5.9710 \times 10^7$	+68.62	Applied manure	7.3470×10^7	6.7662×10^7	-5.8080×10^6	−7.91
Area-weighted mean urban patch size[a]	109	182	73	+66.97	Area-weighted mean non-agricultural/non-urban patch size[a]	6629	2398	−4.231	−63.83
					Area-weighted mean urban patch size[a]	109	182	73	+66.97
Percentage of extractive land	0.21	0.16	−0.05	−23.81	Percentage of barren land within the riparian stream buffer	0.43	0.35	−0.08	−18.60
Area-weighted mean edge contrast of deciduous forest	31.84	28.34	−3.50	−10.99					
Percentage of cropland	10.05	8.68	−1.37	−13.63					
Percentage of evergreen forest within the riparian stream buffer	5.66	5.31	−0.34	−6.18					

[a] The averaged value of these land-based source variables from all 2339 catchments.

Table 4
Comparison of 2000 and projected 2030 Chesapeake Bay watershed-wide total loadings (kg/year) delivered to the estuary from all significant sources and mean yield (kg/ha/year) from all 2339 catchments.

TN model					TP model				
Variable	2000	2030	2030–2000 change	2030–2000 % change	Variable	2000	2030	2030–2000 change	2030–2000 % change
Point	4.4105×10^7	5.2200×10^7	$+8.0950 \times 10^6$	+18.35	Point	1.9665×10^6	2.3677×10^6	$+4.0120 \times 10^5$	+20.40
Applied fertilizer	4.8395×10^7	1.5615×10^7	-3.2780×10^7	−67.73	Applied fertilizer	1.0226×10^6	5.4169×10^5	-4.8091×10^5	−47.03
Applied manure	9.7110×10^6	1.2783×10^7	$+3.0720 \times 10^6$	+31.63	Applied manure	5.2862×10^5	4.8027×10^5	-4.8350×10^4	−9.15
Atmospheric deposition	3.5803×10^7	2.7355×10^7	-8.4480×10^6	−23.60	Area-weighted mean non-agricultural/non-urban patch size	1.5772×10^6	5.0174×10^5	-1.0755×10^6	−68.19
Area-weighted mean urban patch size	6.9311×10^6	9.1806×10^6	$+2.2495 \times 10^6$	+32.46	Area-weighted mean urban patch size	2.7222×10^5	4.0387×10^5	$+1.3165 \times 10^5$	+48.36
Total	1.4495×10^8	1.1713×10^8	-2.7820×10^7	−19.19	Total	5.3671×10^6	4.2953×10^6	-1.0718×10^6	−19.97
Point	16.43	16.98	+0.55	+3.35	Point	0.79	0.82	+0.03	+3.80
Applied fertilizer	3.84	1.01	−2.83	−73.70	Applied fertilizer	0.08	0.04	−0.04	−50.00
Applied manure	0.42	0.75	+0.33	+78.57	Applied manure	0.03	0.03	+0.00	+0.00
Atmospheric deposition	2.39	1.91	−0.48	−20.08	Area-weighted mean non-agricultural/non-urban patch size	0.11	0.04	−0.07	−63.64
Area-weighted mean urban patch size	0.85	0.84	−0.01	−1.18	Area-weighted mean urban patch size	0.03	0.04	+0.01	+33.33
Total	23.93	21.49	−2.44	−10.20	Total	1.04	0.97	−0.07	−6.73

Table 5
Comparison of 2000 and projected 2030 Chesapeake Bay watershed-wide total loadings (kg/year) delivered to the estuary from all significant sources and mean yield (kg/ha/year) from all 2339 catchments with prediction errors for each year, range of 2030–2000 change, and range of 2030–2000 % change.

TN model

Variable	2000	2030	2030–2000 change	2030–2000 % change
Point	$4.4105 \times 10^7 \pm 1.0612 \times 10^7$	$5.2200 \times 10^7 \pm 1.2559 \times 10^7$	-1.5076×10^7 to $+3.1266 \times 10^7$	−27.55 to +93.35
Applied fertilizer	$4.8395 \times 10^7 \pm 1.1644 \times 10^7$	$1.5615 \times 10^7 \pm 3.7570 \times 10^6$	-4.8181×10^7 to -1.7379×10^7	−80.25 to −47.29
Applied manure	$9.7110 \times 10^6 \pm 2.3365 \times 10^6$	$1.2783 \times 10^7 \pm 3.0756 \times 10^6$	-2.3401×10^6 to $+8.4841 \times 10^6$	−19.42 to +115.05
Atmospheric deposition	$3.5803 \times 10^7 \pm 8.6142 \times 10^6$	$2.7355 \times 10^7 \pm 6.5816 \times 10^6$	-2.3644×10^7 to $+6.7478 \times 10^6$	−53.23 to +24.82
Area-weighted mean urban patch size	$6.9311 \times 10^6 \pm 1.6676 \times 10^6$	$9.1806 \times 10^6 \pm 2.2089 \times 10^6$	-1.6270×10^6 to $+6.1260 \times 10^6$	−18.92 to +116.39
Total	$1.4495 \times 10^8 \pm 3.4875 \times 10^7$	$1.1713 \times 10^8 \pm 2.8181 \times 10^7$	-9.0876×10^7 to $+3.5236 \times 10^7$	−50.54 to +32.01
Point	16.43 ± 3.95	16.98 ± 4.09	−7.49 to +8.59	−36.74 to +68.83
Applied fertilizer	3.84 ± 0.92	1.01 ± 0.24	−4.00 to −1.66	−83.90 to −57.03
Applied manure	0.42 ± 0.10	0.75 ± 0.18	+0.05 to +0.61	+9.31 to +191.72
Atmospheric deposition	2.39 ± 0.58	1.91 ± 0.46	−1.51 to +0.56	−51.08 to +30.56
Area-weighted mean urban patch size	0.85 ± 0.20	0.84 ± 0.20	−0.42 to +0.40	−39.51 to +61.44
Total	23.93 ± 5.76	21.49 ± 5.17	−13.37 to +8.49	−45.03 to +46.71

TP model

Variable	2000	2030	2030–2000 change	2030–2000 % change
Point	$1.9665 \times 10^6 \pm 6.3243 \times 10^5$	$2.3677 \times 10^6 \pm 5.6991 \times 10^5$	-9.9268×10^5 to $+1.7951 \times 10^6$	−38.20 to +134.56
Applied fertilizer	$1.0226 \times 10^6 \pm 3.2887 \times 10^5$	$5.4169 \times 10^5 \pm 1.3038 \times 10^5$	-9.8399×10^5 to $+2.2166 \times 10^4$	−72.81 to +3.20
Applied manure	$5.2862 \times 10^5 \pm 1.7000 \times 10^5$	$4.8027 \times 10^5 \pm 1.1560 \times 10^5$	-3.7281×10^5 to $+2.7611 \times 10^5$	−53.64 to +76.99
Area-weighted mean non-agricultural/non-urban patch size	$1.5772 \times 10^6 \pm 5.0723 \times 10^5$	$5.0174 \times 10^5 \pm 1.2077 \times 10^5$	-1.7440×10^6 to -4.0687×10^5	−83.67 to −38.03
Area-weighted mean urban patch size	$2.7222 \times 10^5 \pm 8.7546 \times 10^4$	$4.0387 \times 10^5 \pm 9.7212 \times 10^4$	-8.5781×10^4 to $+3.4908 \times 10^5$	−23.84 to +189.03
Total	$5.3671 \times 10^6 \pm 1.7261 \times 10^6$	$4.2953 \times 10^6 \pm 1.0339 \times 10^6$	-4.1792×10^6 to $+2.0356 \times 10^6$	−58.92 to +55.91
Point	0.79 ± 0.25	0.82 ± 0.20	−0.48 to +0.54	−46.72 to +102.21
Applied fertilizer	0.08 ± 0.03	0.04 ± 0.01	−0.08 to +0.00	−74.33 to −2.59
Applied manure	0.03 ± 0.01	0.03 ± 0.01	−0.20 to +0.20	−48.67 to +94.81
Area-weighted mean non-agricultural/non-urban patch size	0.11 ± 0.04	0.04 ± 0.01	−0.12 to −0.02	−81.33 to −29.16
Area-weighted mean urban patch size	0.03 ± 0.01	0.04 ± 0.01	−0.01 to +0.03	−31.56 to +159.75
Total	1.04 ± 0.33	0.97 ± 0.23	−0.72 to +0.58	−52.12 to +81.70

2.3. Projected fertilizer and manure applications and point source loadings

The values of those source loading variables that were significant in the TN and TP models that are subject to LC/LU change, such as fertilizer and manure applications and point source loadings, were projected forward to 2030. The 2000 atmospheric deposition of N was unchanged since the aim of this work was to determine the effects of urbanization on source loadings and because of the difficulty in forecasting a variable that is largely determined by policy, regulation, and legal changes.

The 2030 annual commercial fertilizer and manure loadings were only considered for pasture and row-crop (croplands), as in the simulations by Brakebill and Preston (2004). This was done to ensure consistency with Brakebill and Preston, since SPARROW is subject to changes in model structure; for example the number of source or land-to-water delivery variables found to be significant may change if the models are calibrated with new datasets. Fertilizer and manure application rates used in the Phase 5.0 Hydrologic Simulation Program FORTRAN (HSPF) Chesapeake Bay model (Chesapeake Community Modeling Program, 2008) were used. These data provided fertilizer and manure loading rates in terms of several chemical forms of N and P, applied to crop and pasture lands within 1000 watershed segments. Fertilizer was defined as applications of ammonia-N (NH_3N) and/or nitrate-N (NO_3N) for N and phosphate-P (PO_4P) for P. Manure was defined as applications of ammonia-N (NH_3N), nitrate-N (NO_3N), and/or organic N for N and phosphate-P (PO_4P) and/or organic P for P. The data also included several management strategies (high till, low till, no till, and nutrient management) used on cropland and pasture for each month in the year. From these data, annual mean applied rates of N fertilizer were calculated; 28.02 and 15.83 kg/ha/year, for cropland and pasture, respectively, whereas P fertilizer had rates of 17.19 and 5.16 kg/ha/year, for these same cover types. Annual mean applied manure rates for N manure were 9.79 and 52.74 kg/ha/year, for cropland and pasture. Finally, P manure rates used for cropland and pasture were 5.56 and 23.77 kg/ha/year.

Using the 2030 areas of cropland and pasture in all of the 2339 model catchments, 2030 annual fertilizer and manure application loadings were tabulated. To determine the total 2030 fertilizer and manure application loadings of N and P, cropland and pasture quantities per catchment were combined. The 2000 and projected 2030 watershed-wide estimates of fertilizer and manure applications are given in Table 3.

Population throughout the watershed in 2030 was predicted for each catchment using an empirical correlation of population with SLEUTH ISA output transformed to housing density (United States Geological Survey, 2008b). For 2000, a non-urban land density of 0.0615 housing units/acre and an urban land density of 2.1 housing units/acre were used.

$$\log(\text{population density}) = 3.18 + \log(\text{housing density}) \quad (1)$$

Utilizing Eq. (1), these housing densities lead to population densities of 93 people per square mile for non-urban land and 3178 people per square mile for urban land. The 2000 population of the Chesapeake Bay watershed was 15,710,840 (Chesapeake Bay Program, 2008a) while the estimate using Eq. (1) was 15,761,476 only 0.003% higher than the official tally. To project population densities in 2030 based upon housing densities, a non-urban land density of 0.0615 housing units/acre was once again used. However, a lower housing density of a 1.5 housing units/acre replaced the 2000 urban land value to represent the effect of continued increases in area occupied by each dwelling. These housing densities lead to population densities of 93 people per square mile for non-urban land and 2270 people per square mile for urban land in 2030. Thus, the population estimated for 2030 was 19,761,581, quite similar to the near 20 million estimate made for the catchment as a whole by the Chesapeake Bay Program (2008b). Eq. (1) was preferred, rather than whole-catchment estimates of future population, since the modeling was based on populations in each of the 2339 catchments, not a single, Chesapeake Bay watershed-wide projection.

Recent wastewater treatment plant (WWTP) estimates show that, on average, 2.72 and 0.16 kg/year of N and P are discharged per person into the watershed (Cummins, 2004). Using the projected urban population gains, in conjunction with these discharge values, provided estimates for 2030 N and P point source loadings (kg/year) from each catchment with municipal WWTPs discharging into Chesapeake Bay waterways, as of 2000. For the 2339 catchments, all estimated increases in point discharges were then assigned to their nearest WWTP for 2030 projections. A comparison of 2000 to the projected 2030 estimated increase in the point source N and P loadings discharged to streams draining the Chesapeake Bay is shown in Table 3.

3. Results

3.1. TN

TN annual loadings predicted to be delivered to the Chesapeake Bay by 2030 were 1.171×10^8 kg/year, as compared to 1.449×10^8 kg/year estimated in 2000 (Roberts and Prince, in press), about 19% less than the 2000 quantity (Table 4). Using the root mean square error (RMSE) of the TN model (0.2406) (Table 2), uncertainties of the model predictions were obtained and indicated that this projected 19% reduction in total loadings was well within the range of change that predicted total loadings could of decreased by as much as over 50% or increased by upwards of 32% between 2000 and 2030 (Table 5). The highest increases in projected TN yield (>4 kg/ha/year) were predicted near: Harrisburg, Lancaster and York (PA); the northern and the eastern shore of MD; DE; and central VA (Fig. 3a). Catchments with the largest decreases in projected TN yield (>4 kg/ha/year) were predicted near Baltimore (MD) and DC (Fig. 3a). A comparison of the six largest basins—the James (27,019 km^2), Patuxent (2479 km^2), Potomac (38,000 km^2), Rappahannock (7405 km^2), Susquehanna (71,225 km^2), and York (6915 km^2 basin formed by the confluence of the Mattaponi and Pamunkey in southeastern VA) from 2000 to 2030 indicated that annual TN loadings in three of these basins (the James, Patuxent, and Rappahannock) were predicted to be increased, while the others decreased. In all six basins, the overall annual TN loadings were predicted to decrease by nearly 17% from 1.1001×10^8 in 2000

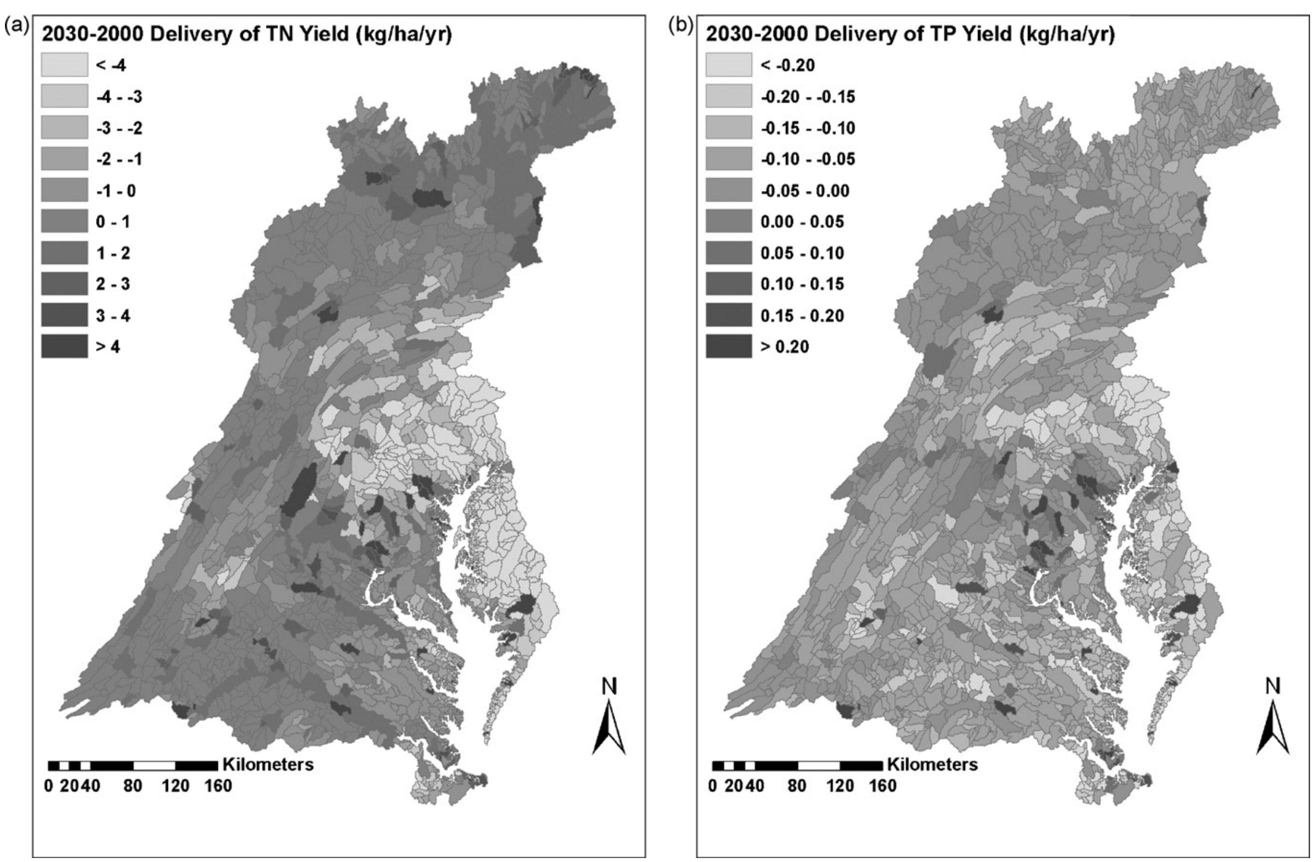

Fig. 3. Per catchment estimated 2030–2000 difference maps of the total yield in kg/ha/year per year for (a) N and (b) P delivered to the Chesapeake Bay.

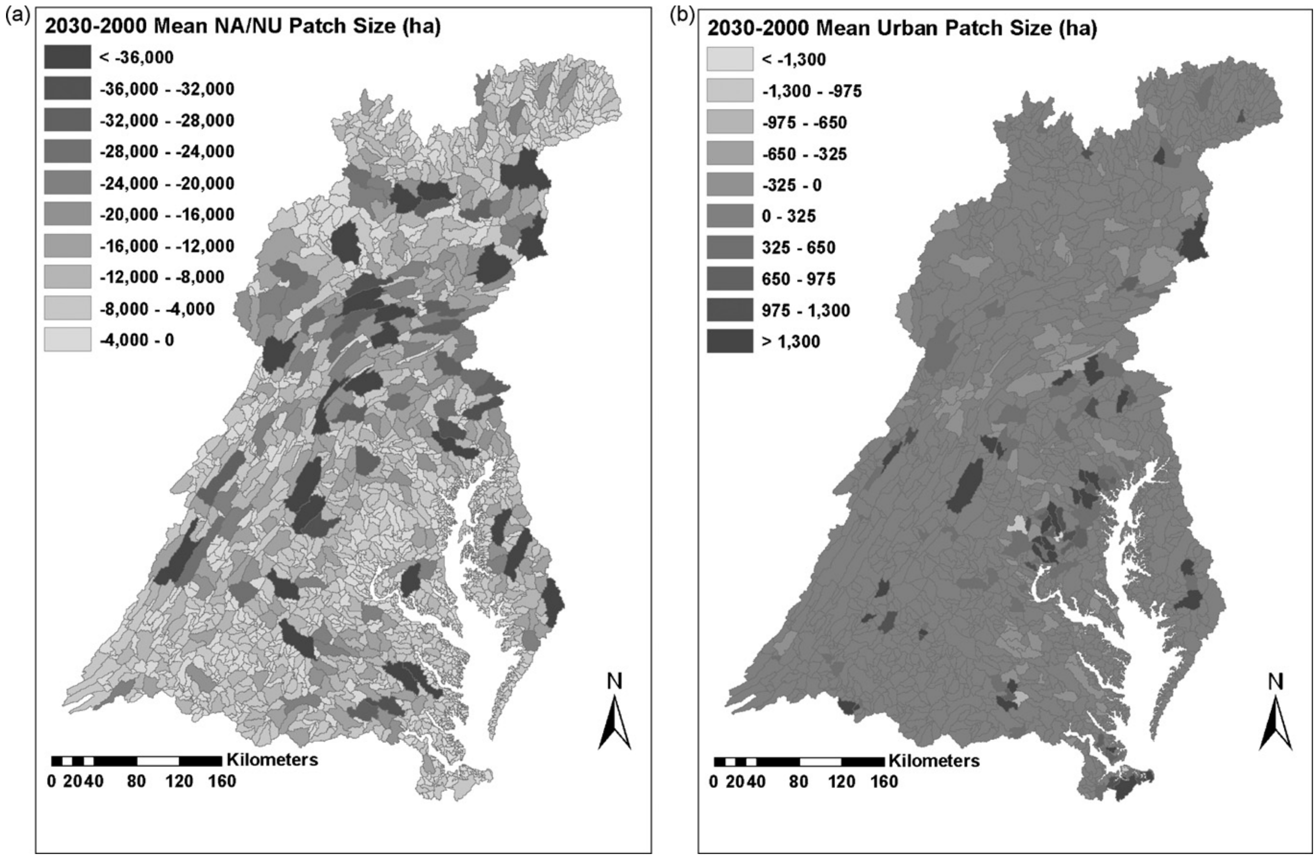

Fig. 4. Per catchment 2030–2000 difference maps of the area-weighted mean: (a) non-agricultural/non-urban (NA/NU) and (b) urban (≥10% ISA) patch size source metrics in ha.

to 9.1776×10^7 by 2030 and were close to the Chesapeake-wide projected decline of 19%.

3.2. TP

2030 TP annual loadings projected to reach the Chesapeake Bay estuary were 20% lower (4.295×10^6 kg/year) than the 5.367×10^6 kg/year predicted to enter the estuary in 2000 (Roberts and Prince, in press) (Table 4). Based upon the RMSE for the TP model (0.3216) (Table 2), predictions of model uncertainty for the change in TP loadings indicated that this 20% reduction value was also well within the range of change that predicted total loadings could of decreased by as much as 59% or increased by 56% between 2000 and 2030 (Table 5). Catchments with the highest increases in projected TP yield (>0.20 kg/ha/year) were also near: Harrisburg, Lancaster, and York (PA); northern and the eastern shore of MD; DE; and central VA (Fig. 3b). The largest decreases in projected TP yield (>0.20 kg/ha/year) were predicted to occur in the same regions as the largest decreases in TN yield (Fig. 3b). The annual TP loadings comparison of the watershed's six largest basins from 2000 to 2030 was also predicted to show an overall decline of approximately 21%, with TP loadings decreasing in all individual basins.

4. Discussion

4.1. Agricultural land losses and reductions in total and agricultural non-point loadings

Overall, the 2030 SPARROW modeled results showed that the predicted conversion of agricultural land to urban uses throughout the Chesapeake Bay watershed can be expected to result in significant reductions in delivered TN and TP. Agriculture is currently the single largest contributor of Chesapeake Bay nutrient pollution, representing 39% and 49% of its N and P loadings (Sims and Coale, 2002). Furthermore, since World War II, the geographic intensification of the use of commercial chemical fertilizers and animal agriculture within regions, such as the lower Susquehanna Basin in southeastern PA the eastern shore of MD, and DE, have increased agricultural nutrient runoff to the Chesapeake Bay by substantially increasing N and P available for non-point source runoff to streams. Thus, as a result of the predicted conversion of agricultural (crop and pasture) land and the lower estimated rates of N and P fertilizer loadings to be applied to these remaining lands by 2030, the projected overall reduction in TN and TP seen here result from smaller quantities of fertilizer loadings delivered to Chesapeake Bay streams. Lower applications of fertilizers represented smaller loadings of eroded organic and dissolved inorganic N and P species available on the land surface and in the shallow subsurface for non-point source delivery to the Chesapeake Bay when transported to streams via overland, shallow interflow, and even baseflow runoff processes.

With the recent adoption of agricultural best management practices (BMPs), such as conservation-tillage and off-season (winter) cover crop conservation programs, total applications of commercial fertilizer are expected to decline (Sims and Coale, 2002). Applications of manure are expected to increase or stay similar to 2000 quantities to provide for crop nutrient needs. Both of these trends are incorporated in the projections of total fertilizer and manure loadings applied for 2030 (Table 3) and help explain the overall, estimated 2030 nutrient reduction trends.

Watershed-wide agricultural land was predicted to decrease from approximately 25% in 2000 to 22% in 2030, with the greatest (>9%) decreases predicted to occur in the most intensely farmed catchments of the lower Susquehanna Basin of southeastern PA, the eastern shore of MD, and DE. This finding has great significance since these catchments were also found in the results for 2000 to produce disproportionately the highest TN (>18 kg/ha/year) and TP (>0.99 kg/ha/year) delivered yields to the Chesapeake Bay (Roberts and Prince, in press). This was mainly a product of the substantial, agricultural, non-point source losses associated with the highest applications rates of fertilizer and manure that occurred throughout the watershed. However, by 2030, the mean delivered yield from these highest producing catchments in 2000 was projected to decrease nearly 11% and 1% for TN and TP, respectively. The declines in mean TN and TP yield seen in these 2000 highest producing catchments were correlated with the anticipated substantial decreases in predominantly applied fertilizer N and P.

The results reported here are similar to those of other studies of the effects of development on future nutrient loadings in smaller watersheds. The increase in TN of between 0.13% and 0.21% for the Saint Louis, Missouri region estimated by Wang et al. (2005) from 2005 to 2030 was an effect of their projected extreme urbanization event. Similarly, Tang et al. (2005) evaluated non-point source nutrient loading differences in north-central Michigan from 1978 to 2040 with predicted urbanization and determined that after development, TN and TP losses would also only slightly increase (<3%). As in the previous study, Tang et al. (2005) projected an extreme increase in urban land from 4.2% to 11.5%, nearly 300%, as compared to <200% in the present study. Thus, in both these studies, the small increases on TN and TP runoff were obtained with overwhelming gains in impervious-based runoff to streams. Without these very high changes in imperviousness, the reduction in non-point losses of fertilizer and manure would of lead to declines in TN and TP loadings. Notwithstanding, even though there were gains in non-point N and/or P due to urbanization, much greater nutrient increases were limited by the conversion of agricultural lands that have higher nutrient contribution than urban uses (Tang et al., 2005; Wang et al., 2005).

Bhaduri et al. (2000) utilized a land use simulator to estimate impervious surface growth near Indianapolis, Indiana from 1973 to 1991 and found that, over this period, an 18% increase in impervious areas resulted in a 15% decrease in non-point source TN and TP loadings. The decline in non-point TN and TP loadings was directly attributed to losses of agricultural lands. Furthermore, in Miami, Florida, Tsihrintzis et al. (1996) found that a specific agricultural land area would have significant non-point source TN and TP reductions of 54% and 35%, respectively, if it was entirely converted to urban use. In both of these studies, these reductions were primarily due to the decreases in fertilizer use.

By substantially lowering the amount of estimated, delivered fertilizers and manure through land conversion in those catchments that contributed the most TN and TP, such as those in the lower Susquehanna Basin of southeastern PA, a greater proportional effect on Chesapeake Bay water quality than elsewhere can be expected. In the Susquehanna Basin alone, TN and TP fell by about 33% and 30%, respectively. This finding is quite significant since the Susquehanna Basin contributes about 50% of water that enters the Bay annually (Susquehanna River Basin Commission, 2008), thus even moderate percentage reductions in loadings would significantly reduce TN and TP entering the Bay. Chang (2004) used a land use change model of proposed development from the late 1990s to 2030 in several lower Susquehanna Basin catchments and also found that agricultural land conversion to urban uses decreased overall, non-point source TP loadings. These trends in smaller parts of the watershed support the findings reported here, that, for the entire watershed, the mean delivered yield will decrease by about 10% and 7% for TN and TP from 2000 to 2030 (Table 4).

4.2. Forest (and other non-agricultural and non-urban) land losses and reductions in non-point loadings

Conversion of forest and other non-agricultural and non-urban land areas to development was also found to correlate with the predicted reduction in TP by 2030. P export from these primarily forested regions of the watershed was shown by the yield of area-weighted mean non-agricultural/non-urban patches that indicated larger patches have greater influences on non-point source generation (Roberts and Prince, in press). By 2030, these large, contiguous patches that contributed dissolved inorganic P to streams were predicted to be substantially smaller as a result of development that stopped these infiltration-based P runoff processes. This was seen in the averaged area-weighted mean non-agricultural/non-urban patch size that decreased nearly 64% from 2000 to 2030 (Table 3), in step with a 67% reduction in its mean delivered yield (Table 4), and a 19% decline in overall TP delivered to the Bay (Table 4). The catchments with the largest (>36,000 ha) losses in area-weighted mean non-agricultural/non-urban patch sizes were predicted to occur throughout the watershed (Fig. 4a). Catchments with the highest (>0.27 kg/ha/year) decreases in delivered P yield from this source were predicted to occur only near central VA (Fig. 5).

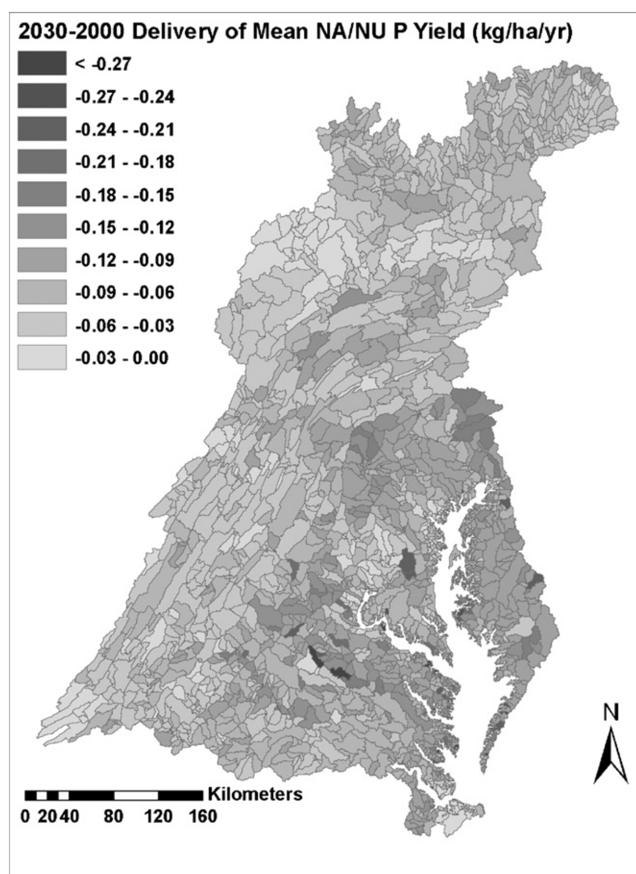

Fig. 5. Per catchment estimated 2030–2000 difference map of the NA/NU patch size yield in kg/ha/year for P delivered to the Chesapeake Bay.

4.3. Impervious surface area gains and changes in urban non-point loadings

As a direct result of increases in urban non-point source loadings, TN was projected to increase in the range of 1–33% from 2000 to 2030 in the James, Patuxent, and Rappahannock Basins. This result is similar to that of Costanza et al. (2002) for the Patuxent, who compared mean delivered TN concentration to the estuary in 1997 with a future "buildout" scenario and found an overall 14% gain. The catchments with the greatest (>2.00 kg/ha/year) increases in non-point urban N yields were near: Baltimore, Cumberland, and Frederick (MD); northeastern WV; DC; and Richmond, Norfolk-Virginia Beach-Newport News, and Lynchburg (VA) (Fig. 6a). Catchments with the largest (>0.08 kg/ha/year) increases in non-point urban P yields were projected to occur in the same regions as urban N with the exceptions of: Cumberland and Frederick (MD) and northwestern WV (Fig. 6b). Catchments with the greatest (>2.00 and >0.08 kg/ha/year) decreases in non-point N and P yields were projected to occur only near DC (Fig. 6b).

Surprisingly, however, from 2000 to 2030, the mean non-point urban N and P yields delivered to the Chesapeake Bay for all 2339 catchments were projected to remain virtually the same, decreasing and increasing by only 0.01 kg/ha/year (Table 4). Non-point urban yields were modeled using area-weighted mean urban ($\geq$10% ISA) patches so that larger patches of development, as opposed to the same area in smaller patches, had greater influences on non-point N and P generation (Roberts and Prince, in press).

The results of the simulation of non-point N and P yields to streams by 2030 are counter-intuitive since the increase in urbanization might have been expected to increase the runoff of nutrients. The expectation of an increase in pollution by urbanization is also suggested by the SLEUTH projections that non-urban LC/LUs will be converted to development from 7% in 2000 to 13% in 2030. The expectation is yet further reinforced since the averaged area-weighted mean urban patch size for all 2339 catchments was predicted to increase by 67% from 2000 to 2030 (Table 3). Catchments with the largest (>1300 ha) increases in area-weighted mean urban patch sizes were predicted to occur near: Harrisburg (PA); Baltimore and Hagerstown (MD); DC; and Richmond, Norfolk-Virginia Beach-Newport News, and Lynchburg (VA) (Fig. 4b). Catchments with the highest (>1300 ha) decreases in this patch size were predicted only near DC (Fig. 4b).

However, TN and TP loadings in streams and reservoirs are attenuated by processes that include denitrification under anaerobic conditions, biological uptake by stream organisms, and sedimentation onto stream and reservoir floors (Alexander et al., 2000). Thus, any increase in non-point N and P discharge from impervious surfaces may be diminished by cumulative downstream water attenuation processes. The greatest increases in imperviousness were predicted to occur in catchments within the small and intermediate stream categories that were estimated to attenuate the highest percentages of instream N loadings throughout the watershed. In the case of P, however, no attenuation occurs in small streams and may explain the overall slight increase in mean delivered P yield projected to the Bay by 2030.

Filoso et al. (2004) found that after the projected conversion of 44% forested land to urban uses from 1991 to 2101 in the Ipswich Basin of Massachusetts, gains in ammonium-N concentrations were trivial (0.2–0.5 μM). The lack of effect on N could have been a result of ammonia volatilization and/or ammonium sorption to sediments within the stream channel (Filoso et al., 2004). Thus,

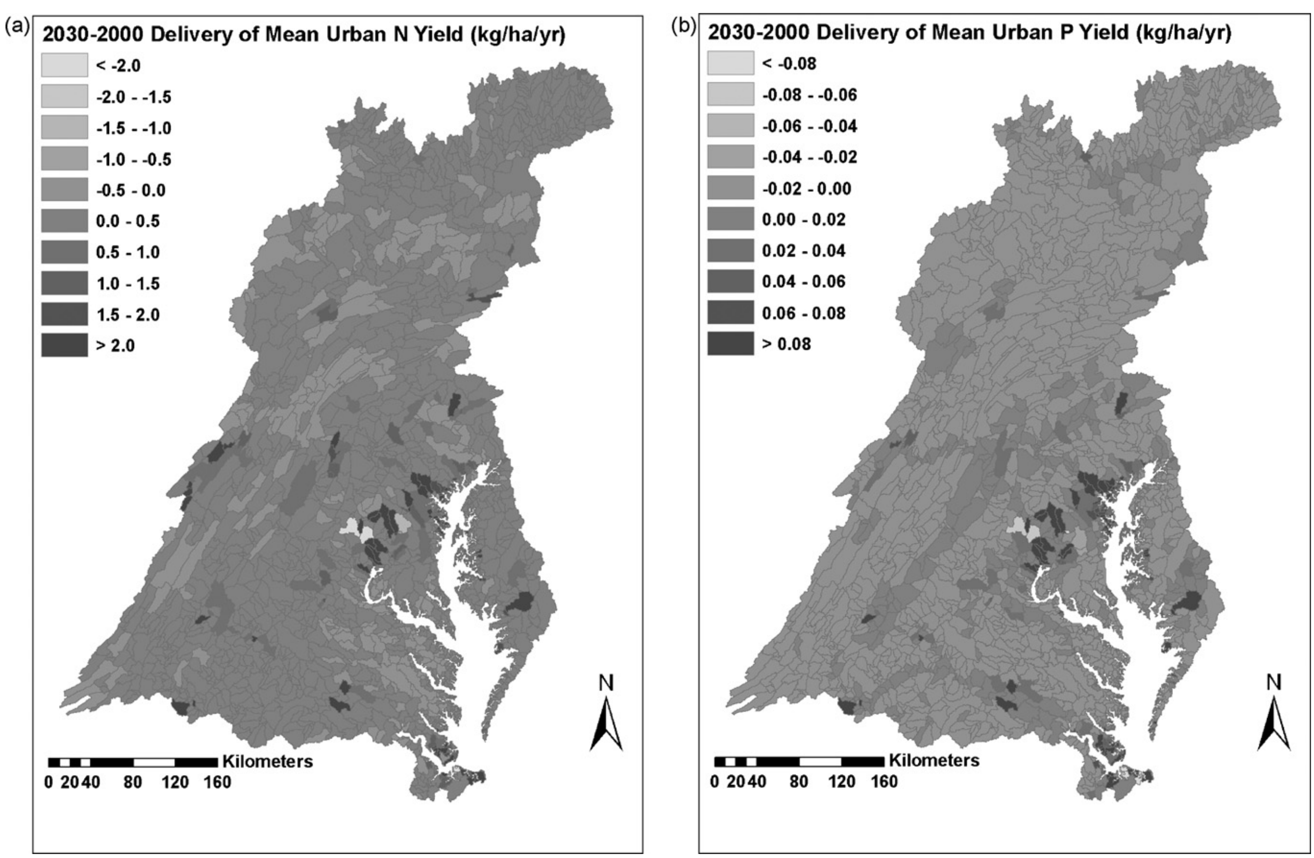

Fig. 6. Per catchment estimated 2030–2000 difference maps of the area-weighted mean urban ($\geq$10% ISA) patch size yield in kg/ha/year for: (a) N and (b) P delivered to the Chesapeake Bay.

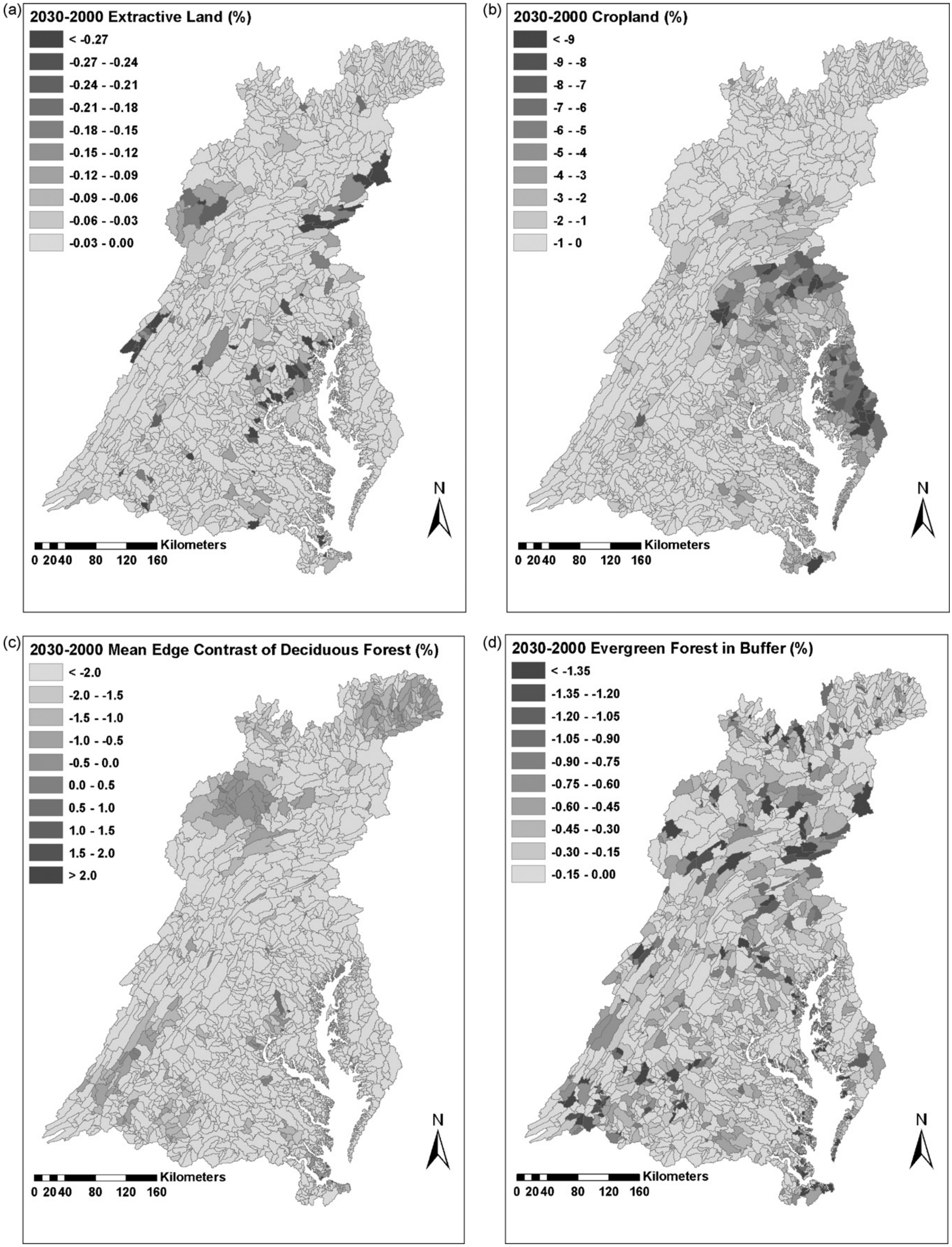

Fig. 7. Per catchment 2030–2000 difference maps of the (a) percentage of extractive land, (b) area-weighted mean edge contrast of deciduous forest land (%), (c) percentage of cropland, and (d) percentage of evergreen forest land in the 31 m riparian stream buffer land-to-water delivery metrics for the TN model.

the expected increases in non-point N, as a result of urbanization, were reduced in part due to significant stream attenuation.

Only in catchments with unusually high rates of estimated urbanization were the projected non-point urban N gains large enough to overwhelm downstream attenuation. Thus, expected substantial gains in mean non-point urban yield delivered to the Bay from 2000 to 2030 did not occur.

4.4. Changes in point sources with urbanization

Gains in population and urban land throughout the watershed must lead to an increase in point source loadings, as well as changes in non-point sources discussed above. Using the models, it was shown that projected increases in delivered point source loadings from 2000 to 2030 would offset the TN and TP loading losses to the Chesapeake Bay caused by non-urban, non-point source reductions. The delivered N and P point loadings to the estuary were projected to increase over 18% and 20%, respectively, between 2000 and 2030 (Table 4). Similarly to the non-point loadings, the only attenuation processes reducing point N and P loadings delivered to the estuary occurred in streams and reservoirs presumably via denitrification, biological uptake, sedimentation, etc.

The negation of the reductions caused by reduction in agriculture, as a result of increases in point sources, must be qualified by recognition of the uncertainties in estimation of future population size and geographical distribution. Furthermore, the projected 2030 discharge additions were based on WWTP estimates of domestic effluent discharge that do not take into account gains or losses from industrial or commercial point sources. Neither do these loadings take into account the future locations of WWTPs, nor any future advances in effluent removal technology that can be expected to decrease these loadings substantially. All of these are limitations of the point loadings with the result that they cannot be quantified with great accuracy.

4.5. Land-to-water delivery losses and reductions in non-urban, non-point loadings

The results indicated that reductions in land-to-water delivery variables, resulting from the conversion of non-urban LC/LUs to development, also contributed to the decreases in delivered TN and TP to the Bay. Roberts and Prince (in press) showed that several landscape metrics were significantly related to increased non-point delivery to Chesapeake Bay streams. For N these were: percentage of extractive land, percentage of cropland, area-weighted mean edge contrast of deciduous forest, and percentage of evergreen forest within the riparian stream buffer and, for P, percentage of barren land within the riparian stream buffer.

The significance of these findings is that changes in the spatial composition and configuration of LC/LU can be expected to provide a means of reduction in land-to-water delivery. Decreases in non-point N and P transport by landscape compositional and configuration changes might be caused by processes such as reduced soil hydraulic conductivity properties and increases in overland and shallow subsurface flow paths (Roberts and Prince, in press). Overland and shallow subsurface flows are favored by compacted or saturated non-urban surfaces often found associated with extractive lands. Croplands, evergreen forests, and barren lands have been shown to have this effect. Stormflow in some Chesapeake Bay tributaries has been suggested to provide pathways for non-point N to reach streams, allowing surface flow to traverse forested riparian buffers (Norton and Fisher, 2000). Changes of LC/LU associated with development may eliminate some surfaces with limited hydraulic conductivity, such as barren land, and contribute to reduction of non-point N and P transport.

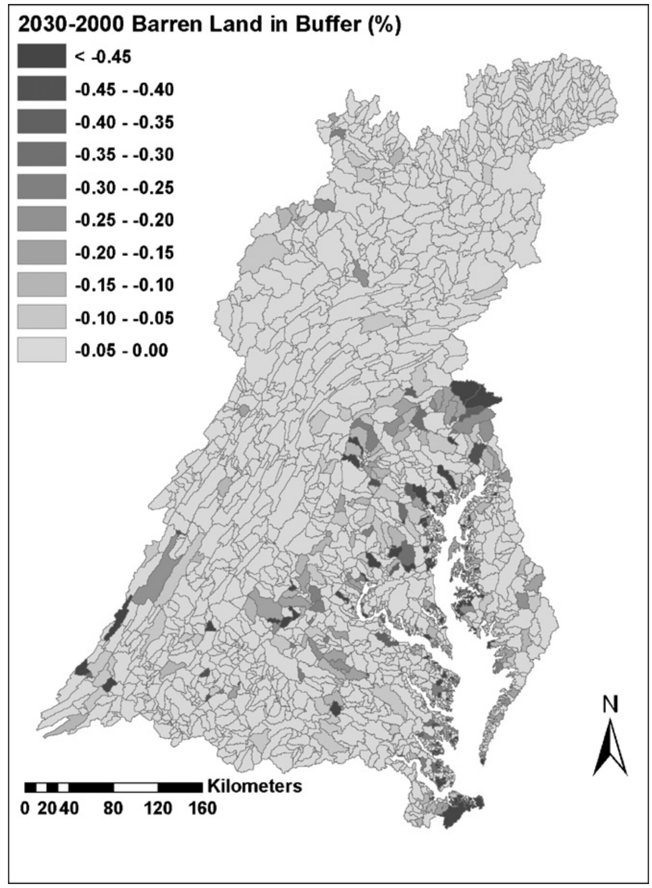

Fig. 8. Per catchment 2030–2000 difference map of the percentage of barren land in the 31 m riparian stream buffer land-to-water delivery metric for the TP model.

The catchments in which significant changes in factors that affect surface and shallow subsurface flow were not evenly distributed across the Chesapeake Bay watershed. The largest decreases (>0.27%) in percentage of extractive land were predicted in: central and east-central PA; western and central MD; northeastern WV; DC; and northern VA (Fig. 7a). Catchments with the greatest (>9%) decreases in percentage of cropland were predicted in: southern PA; the eastern shore of MD; and DE (Fig. 7b). The catchments with the greatest (>2.0%) decreases in area-weighted mean edge contrast of deciduous forest were predicted throughout the watershed, whereas the greatest (>2.0%) increases in area-weighted mean edge contrasts of deciduous forest were predicted near: east-central MD and Norfolk-Virginia Beach-Newport News (VA) (Fig. 7c). Catchments with the largest (>1.35%) decreases in percentage of evergreen forest within the riparian stream buffer were predicted watershed-wide (Fig. 7d). Finally, the catchments with the greatest (>0.45) decreases in the percentage of barren land within the riparian stream buffer were predicted near: Lancaster (PA); Baltimore and Frederick (MD); DC; and Norfolk-Virginia Beach-Newport News (VA) (Fig. 8).

5. Summary and conclusion

Previously, the quantification of the impacts of projected future urbanization on nutrient loading estimates has been limited to smaller watersheds and impacts on regional, national, and even global nutrient loadings have been deduced from the results of local studies. To substantiate the expectations based on the small catchments, substantially larger watersheds regions that drain into large estuaries and coastal oceans need to be examined from the detailed small catchment scale aggregated to the larger catchments in which they occur. The present study of the potential future sources and transport of TN and TP using projections of urbanization in the Chesapeake Bay watershed is an attempt to undertake such an assessment. The effects of LC/LU change from 2000 to 2030 in the Chesapeake Bay watershed, in particular as a result of forecast population increases and consequent increases in urbanization, was modeled and the effects on nutrient loadings to the Bay assessed.

There was an estimated 19% and 20% reduction in overall delivered TN and TP to the Chesapeake Bay. Although substantial increases in development-induced, point source N and P loadings were apparent watershed-wide, the estimated conversion of agricultural lands leading to declines in delivered fertilizer loadings to streams was the primary reason for the overall reductions in TN and TP delivery to the Bay that were simulated to occur from 2000 to 2030. In contrast to the non-point source changes, the projected increases in point source N and P loadings are necessarily imprecise because future improvements in effluent removal technologies, future WWTP locations that could alter their watershed-wide distribution, and possible gains or losses in industrial and commercial sources cannot be predicted. Increases in impervious surfaces associated with urbanization that would otherwise have increased the mean, delivered non-point urban N and P yields for all catchments from 2000 to 2030 were negated due to downstream water attenuation processes decreasing delivered TN and TP to the Bay from all sources.

The relative magnitude of TN and TP contributions by point sources, fertilizers, and other non-point sources to future nutrient loadings depends on the land cover mosaics of a watershed (Anbumozhi et al., 2005), as well as total area. The results suggest that lowering area-weighted mean patch sizes within catchments of significant non-point LC/LU sources could reduce future TN and TP loadings to the Chesapeake Bay. This is especially true of mean urban patch sizes, where decreases in its total area would be likely to limit its yields by reducing impervious surface areas capable of capturing non-point N and P delivered to streams. In addition, limiting urban growth to the replacement of agricultural source lands and other non-urban cover types associated with large land-to-water delivery of non-point N and P to Chesapeake Bay streams would be particularly effective.

Thus, to minimize projected TN and TP loadings to the Chesapeake Bay, the estimated, spatial distribution of LC/LU, at catchment and riparian stream buffer-wide scales, should be examined and evaluated in the future prior to development. This would allow for the maximum impacts of the compositional and configurational landscape properties demonstrated here to be quantified comprehensively.

Acknowledgements

This work was partly sponsored by NASA grant NNG06GC43G.

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